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Modelling of AA6082 ductile damage evolution under hot rolling conditions

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Abstract

Formability is one of the critical issues in metal forming processes since it is a limiting factor for the process parameters choice as well as for the attainable part quality. This issue is of even higher importance in processes carried out at elevated temperature, in which more variables are involved, and the temperature changes can influence the material microstructural behavior, which, in turn, influences the fracture occurrence. The work reported in the paper refers to the hot cross wedge rolling process carried out on AA6082 aluminum alloy bars, which was taken as the reference industrial case. A modification of the Oyane fracture criterion providing the dependency on the temperature and strain rate was developed and calibrated by means of hot tensile tests, which were carried out at varying temperature and strain rate spanning the hot temperature range for the given alloy. Material formability changes were identified and modelled. The calibrated fracture criterion was implemented in the FE model of the industrial process and validated by comparing the numerical and experimental outcomes.

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Keywords: Hot rolling; Hot formability; Ductile damage; Fracture criterion.

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1. Introduction

Finite element simulations are a powerful tool for the design and optimization of industrial forming processes, permitting to reduce cost-intensive prototyping steps and to obtain cheaper and high-quality products. However, FE models require a proper calibration in order to provide accurate and reliable results (Tekkaya, 2005). In particular, formability behavior modeling is crucial in order to avoid crack formation and therefore attain defects-free parts.

The approach to this topic in bulk metal forming consists in applying fracture criteria, usually calibrated through combined experimental and numerical procedures (Skrezypek and Ganczarski, 1999), which can be classified into two main categories, namely uncoupled and coupled criteria. The former do not couple the mechanical behavior of the material with the damage evolution. In this category energy-based, such as in the work of Cockroft and Latham (1968), and void growth-based models, such as in those of Rice and Tracey (1969) and Oyane (1980), fall. The latter couple the material rheological behavior with the damage evolution, and are based either on the modeling of the voids evolution as in the work of Gurson (1977), or on the thermodynamics of the irreversible processes as in the framework of Continuum Damage Mechanics based on the Lemaitre's work (2005). The coupled criteria provide a more detailed physical description of the damage phenomenon and its evolution; they show less dependency on the test results, even if they are more difficult to be calibrated and implemented in FE codes and therefore less suitable for industrial applications. In the last years, the research has been mostly aimed at gaining a deeper comprehension of the influence of the stress state on the damage evolution (Bao and Wierzbicki, 2004), at taking into explicit account the rheological characteristics of the material (Coppola et al., 2009), or at enhancing the capabilities of the coupled criteria (Bonora, 1997). All the above-mentioned modeling approaches were originally developed for cold deformation conditions, neglecting any influence of the temperature and strain rate.

On the contrary, the prediction of the material formability becomes mandatory especially when the hot forming process provokes high temperature gradients, which may result in the overcome of the temperature limits of the forgeability window as well as in the occurrence of microstructural events lowering the material formability. Ghiotti et al. (2009) modified the Lemaitre model to evaluate the microstructural dependency under hot, but isothermal, forming conditions. Hurtado and Morales (2001) carried out an experimental investigation on the influence of temperature and strain rate on both the material formability and fracture modes, while, more recently, Khan et al. (2012) proposed an analytical approach to model the influence of temperature and strain rate on the formability. Zhu et al. (2012) proposed a simple procedure for the prediction of the surface cracking in hot compression tests and He et al. (2013) presented a work in which the Oyane criterion was extended to high temperatures. However, all these research works based their validation on simple cases, such as tensile or compression tests, where the temperature changes during deformation were almost negligible and did not cause any evident microstructural evolutions. In fact, the formability increase with the temperature is not a univocal trend, since thermal conditions also affect the material microstructural behavior and thus the fracture occurrence itself. One of the main research challenges in metal forming is then to develop new fracture criteria that depend explicitly on temperature and strain rate, capable to predict the occurrence of fracture also in fracture-mode-change regimes.

The work presented in this paper proposes the modification of the conventional Oyane fracture criterion by taking into account the influence of the temperature and strain rate on the material damage evolution. A hot cross wedge rolling process of AA6082 alloy round bars was chosen as the reference industrial case. Hot compression tests were carried out in order to determine the rheological behavior of the material, while a tensile test campaign on smooth specimens was performed under the same thermo-mechanical conditions in order to assess the material formability. The Oyane criterion in its conventional formulation was calibrated at fixed temperature and strain rate by means of FE simulations. The conventional formulation of the Oyane criterion was then modified by introducing a function of the temperature and strain rate allowing the normalization of the trigger value to a unitary value. The new formulation was implemented in the numerical model of the reference process and validated by comparing the experimental and numerical outcomes. The comparison clearly evidenced that the proposed fracture criterion permitted to capture the drop in the material formability and the consequent fracture occurrence at the rolled bar axis that was evidenced during the industrial trials carried out at the highest temperature.

2. Industrial case study

In the present work the hot cross wedge rolling of AA6082-T6 aluminium alloy round bar is taken as the reference industrial case to investigate the alloy formability behaviour at varying temperature and strain rate. This process is used to produce semi-finished parts for automotive components by the action of two rolls with shaped surfaces. It allows having high productivity, satisfactory geometrical precision and low material waste. Thus, it has become one of the main options to produce semi-finished parts. Axial cracking, particularly difficult to detect, represents a typical defect due to the Mannesmann effect arising at the bar axis (Li and Lovell, 2008).

The round bar having 48 mm in diameter and 400 mm in length is heated in an electric furnace, in which it reaches the process temperature, spanning in the range between 400 and 550 °C. The bar is then manually mounted on the rolling mill and hot worked in a single roll turn with a rotation speed comprised between 2 and 4 rpm. During the transfer, the bar surface temperature was monitored through an infra-red thermocamera proving that the temperature loss in the 5 s of handling time was negligible; therefore, it can be assumed that the bar temperature at the process starting was the same of the heating stage. Industrial trials conducted at bar heating temperatures higher than 500°C showed the formation of cracks at the bar axis.

3. Laboratory experiments

Compression and tensile experiments were performed on a Gleeble 3800^{TM} thermo-mechanical simulator at varying temperature and strain rate. The former were carried out to calibrate the material mechanical behavior using the Hansel Spittel model; the latter were performed to investigate its formability limits. In both types of tests, the specimens were heated by Joule effect and their temperature was controlled through K-thermocouples spot-welded on the gauge length. The heating rate and the soaking time were kept constant for all the testing conditions, while the testing temperature and strain rate were varied. A FE numerical model of the tensile test was also developed to provide the basis for the inverse analysis procedure devoted to the calibration of the fracture criterion.

Table 1 shows the experimental plan for the compression and tensile tests. Preliminary numerical simulations of the process were carried out to estimate the involved strain rates: values between 0.4 and 0.8 s^{-1} were found.

Table 1. Experimental plan of compression and tensile tests.

Test parameter	Compression test	Tensile test
Heating rate [°C/s]	10	10
Soaking time [s]	180	180
Testing temperature [°C]	400, 500, 550	400, 500, 550
Strain rate [s^{-1}]	0.1, 1	variable
Ram speed [mm/s]	variable	1, 10
Repeatability	2	2

The tensile tests were carried out until rupture of the specimen under the same thermo-mechanical conditions applied in the compression tests. Nominal strain rate values of 0.1 s^{-1} and 1 s^{-1} were attained with constant ram speeds. Thermal measurements allowed identifying the length of the specimen that actually undergoes most of the deformation (see Fig. 1), in order to set the proper ram speed values.

T_{test} [°C]	$\dot{\varepsilon}_{nom}$ [s^{-1}]	D_f [mm]
400	0.1	2.98
400	1.0	2.38
500	0.1	3.06
500	1.0	2.10
550	0.1	3.30
550	1.0	4.28

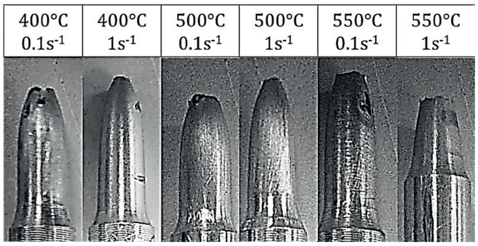

Fig. 1. Diameters at fracture of the tensile test specimens as a function of the testing parameters.

The diameter at fracture was chosen as formability index to calibrate the fracture criterion, since it is not affected by thermal non-uniformities outside the gauge length. The diameter at fracture was measured by means of optical microscopy; the resulting values are reported in the table of Figure 1 with the images of the fractured specimens during the tensile tests. Both the table and the images clearly show that at lower testing temperatures the material shows a higher formability, while the strain rate influence is not univocal.

The FE model of the tensile test was developed using the commercial FE code FORGE®, as shown in Fig. 2. A sensitivity analysis on the mesh dimension was performed, resulting in an optimal mesh size of 0.5 mm.

Simulation parameter	Value
Simulation type	2D
Mesh size [mm]	0.5
Number of elements	~12000
Material model	viscoplastic, Hansel-Spittel
Temperature	see figure
HTC with air [W/m^{2}K]	10

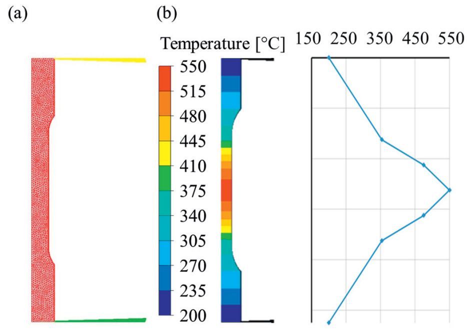

Fig. 2. Simulation parameters and FE model of the tensile test, (a) mesh, and (b) temperature distribution.

The simulations results permitted to evaluate the actual evolution of the strain rate in the specimen region where the necking occurs, due to strain localization. The average values of the strain rate (reported in the table of Figure 3), were chosen as the strain rate values to be later on utilized in the criterion calibration procedure.

4. Modification of Oyane fracture criterion

The occurrence of cracks at the bar axis in a cross wedge rolling process has been recently modeled under cold conditions by using the normalized Cockroft and Latham criterion (Wang et al., 2009). This criterion, however, does not take into account the influence of the triaxiality, which was proved to be high at the bar axis in case of processes showing the Mannesmann effect (Ghiotti et al., 2009). In the present study, the Oyane fracture criterion was chosen as the basis for the damage modeling, since it accounts for the triaxiality dependency and has proved to be effective for high triaxiality values.

T_{test} [°C]	$\dot{\varepsilon}_{avg}$ [s^{-1}]	$ø_f$ [mm]	D_{Oy}^*[-]
400	0.2	2.98	2.95
400	2.57	2.38	4.41
500	0.13	3.06	2.68
500	1.75	2.10	4.24
550	0.1	3.30	2.37
550	1.0	4.28	1.30

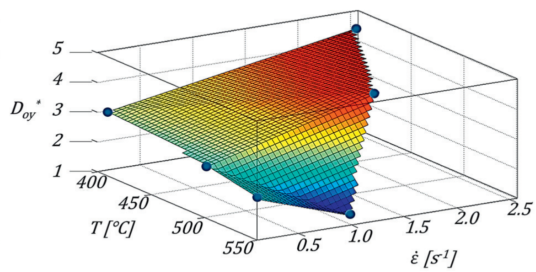

Fig. 3. Oyane critical damage parameters and fracture locus as a function of the temperature and strain rate.

For each of the thermo-mechanical testing conditions the identification provided the Oyane critical damage D_{Oy}^* when the specimen diameter at the necking region in the numerical simulation was equal to the experimental one. In Fig. 3 the results of the calibration are highlighted. It is worth to underline that the values of the critical damage D_{Oy}^{*} are strongly dependent on the temperature and strain rate in the investigated ranges: if constant values of the critical damage were used in the simulation of processes characterized by significant thermal gradients, this would force to apply values of the critical damage lower than needed in order to assure safe numerical predictions.

To overcome this limitation, with the aim of having a more accurate model to predict ductile fracture under hot deformation conditions, a modification of the Oyane criterion is proposed, which takes into account the temperature and strain rate influence on the material formability. Eq. (2) expresses this modification with the introduction of a function of the temperature and strain rate $f(T,\dot{\varepsilon})$, which makes it possible to describe the material behavior under non-isothermal and varying strain rate conditions.

$$D_{new} = \int_0^{\bar{\varepsilon}} f(T,\dot{\varepsilon}) \left(1 + B\frac{\sigma_H}{\bar{\sigma}}\right) d\bar{\varepsilon}. \qquad (2)$$

The function f can assume different shapes and its definition it is not univocal. In this work the formulation showed in Equation 3 is proposed.

$$f(T,\dot{\varepsilon}) = \frac{1}{D_{Oy}^{*}(T,\dot{\varepsilon})}. \qquad (3)$$

In which $D_{Oy}^{*}(T,\dot{\varepsilon})$ is the linear interpolation of the Oyane critical damage values (see the graph in Figure 3). The direct consequence of this assumption is that, for all the tested conditions, the critical damage value D_{new}^{*} assumes a value equal to 1, providing the normalization of the damage trigger value.

5. Validation

The numerical model of the hot cross wedge rolling process was set up to provide the validation of the proposed approach; the novel fracture criterion was implemented in the FE code with an expressly developed subroutine. In Figure 4 the cross wedge rolling FE model parameters are summarized along with the validation results. The two initial temperatures of the bar were the ones actually applied during the industrial trials as well as the roll rotation speed. These, therefore, represent the processing conditions for validating the new approach.

Simulation parameter	Value
Bar initial diameter [mm]	48
Bar initial length [mm]	400
General mesh size [mm]	4
Axial remesh box diameter [mm]	15
Mesh size in the remesh box [mm]	1.0
Number of elements	~25000
Initial bar temperature [° C]	445, 510
Roll rotation speed [rpm]	3
Roll temperature [° C]	240
Friction model	Tresca, m=0.5
Material model	Hansel-Spittel model
HTC with air [W/m²K]	10
HTC with dies [W/m²K]	2500

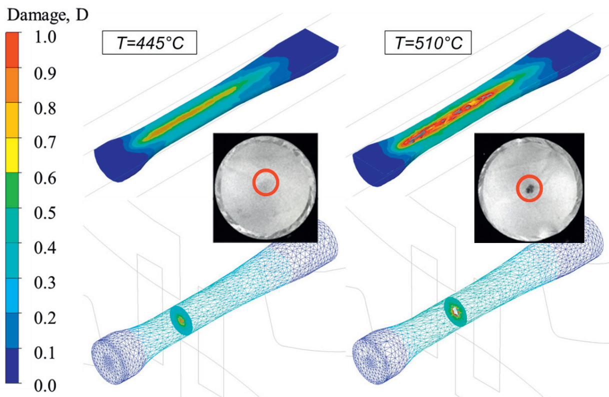

Fig. 4. Cross wedge rolling simulation parameters and comparison between numerical and experimental results.

In Fig. 4 the comparison between the numerical and experimental cross sections of the bar is shown: the numerical model predicts the axial cracking for the higher temperature, while, at 445 °C, the damage value at the end of the rolling process is equal to 0.82 and therefore the bar does not crack. Thus, the comparison between the numerical results and the industrial trials outcomes proved that the modified Oyane fracture criterion calibrated by means of the developed procedure is capable of capturing the change in the AA6082 formability as a function of the temperature and strain rate.

6. Conclusions

The paper has proposed a modification of the Oyane fracture criterion, which takes into account the influence of the temperature and strain rate, and has proved its capability to model the damage evolution during a metal forming process carried out at elevated temperature. The proposed model was validated in the case of a hot cross wedge rolling process carried out on AA6082-T6 bars. The modification of the Oyane criterion consisted in the introduction of a function of the temperature and strain rate, obtained by linear interpolation on the basis of the critical damage values according to the conventional Oyane fracture criterion. These critical values were identified through a combined experimental and numerical procedure, making use of tensile tests carried out at elevated temperature and varying strain rate. The novel fracture criterion was then implemented in the FE numerical model of the hot cross wedge rolling process. The comparison between the experimental and numerical results proved a satisfactory replication of the cracks appearing at the bar axis when rolled at high temperature.

The proposed approach shows the following main advantages:

- it allows describing the damage evolution in conditions of varying temperature and strain rate, providing a unique trigger value for the failure occurrence;
- it is analytically easy to be implemented in a FE code, and does not require further experimental data if compared with the standard Oyane's criterion;
- it allows normalizing the damage critical value, which is a feature that can prove to be useful if the damage coupling with the mechanical characteristics is further required.

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